INVESTIGATION ON TRANSIENT COMBUSTION AND PM EMISSIONS OF DIESEL ENGINE

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For obtaining the optimal switching control strategy and reducing PM (particulate matter) emissions during the controlled turbocharger switch-in process, transient combustion and PM emissions of the sequential turbo-charging diesel engine are investigated in this work. In the transient experiments, the diesel engine performance parameters and PM emissions are measured when the delay time between air valve and gas valve open is 0s, 0.5s, 1.5s and 2.5s during the controlled turbocharger switch-in process. The experiment results show that the air reversed flow appeared in the controlled turbocharger and the PM emission deteriorated when the air valve and gas valve are open simultaneously. However, with extending switching delay time, engine speed waved obvious and main turbocharger pressure dropped. It is also shown that the engine combustion and transient PM emissions get worsened by the long delay time. Optimal control strategy is obtained during the switch-in process of controlled turbocharger under a switching point. During the controlled turbocharger switch-in process, the air valve should open 0.5s later than the gas valve. This strategy can effectively reduce the PM emissions in the transient switching process.

Keywords: Combustion, PM Emissions, Transient Switching Strategy, Delay Time, Diesel Engine.

1. Introduction

With the continuous development of the diesel engines of high power density and wide speed range, the requirements for the turbocharger systems to match the diesel engines are also increased. STC (sequential turbo-charging) system is an effective measure to improve the fuel economy and the transient responsive performance [1-6]. The basic working principle of sequential turbo-charging system is that multiple turbochargers are put into operation in sequence with the increase of the engine speed and load, so as to ensure the working turbochargers are always running in the high-efficiency region. The current STC system generally has two turbochargers, main turbocharger and controlled turbocharger. The low load

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performance of the diesel engine is obviously enhanced when the diesel engine only works with the main turbocharger in low load condition.

Some of the studies of STC system, which have made significant achievements, are about steady operation performance or the determination of engine speed for the switching process of STC system [7-13]. However, during the controlled turbocharger switch-in process, the air valve must be opened later than gas valve and the incorrect delay time will make the controlled turbocharger surge. So the proper switching delay time of controlled turbocharger at switch-in process is very important [14-16]. Moreover, reducing the PM emission, especially in transient switching, has become more significant with the more stringent regulation on PM emissions[17-19]. In this study, the transient switching experiments of the STC system are carried out to obtain the optimal switching control strategy and reduce PM emissions during the controlled turbocharger switch-in process.

2. Experimental Setup

The engine in the present study is a twelve-cylinder, four-stroke, direct injection, water cooled and turbocharged diesel engine. There are two turbocharger systems in the engine, main turbocharger and controlled turbocharger respectively. For working efficiently in the low condition of the engine, the two turbochargers systems are put into operation in sequence with the increase of the engine speed and load. The transient switch progress can be controlled by air valve and gas valve. The main parameters of the STC diesel engine are outlined in Table 1.

Table.1

Engine Specifications

Bore(mm)	128
Connect rod length(mm)	255
Rated speed(r/min)	1800
Rated power(kW)	222
Number of nozzle orifices	4
The switching condition	1429r/min and 50% load

The structure sketch of the sequential turbo-charging system is shown in Fig.1. In this turbo-charging system, the type of the main and the controlled turbochargers both are J100, the air valve is set after the controlled compressor and the gas valve is set before controlled turbine. When the engine operates at low load condition, the main turbocharger works only (1TC). With the engine speed increasing, the gas valve and the air valve are both open, so the main and the controlled turbochargers simultaneous work (2TC).

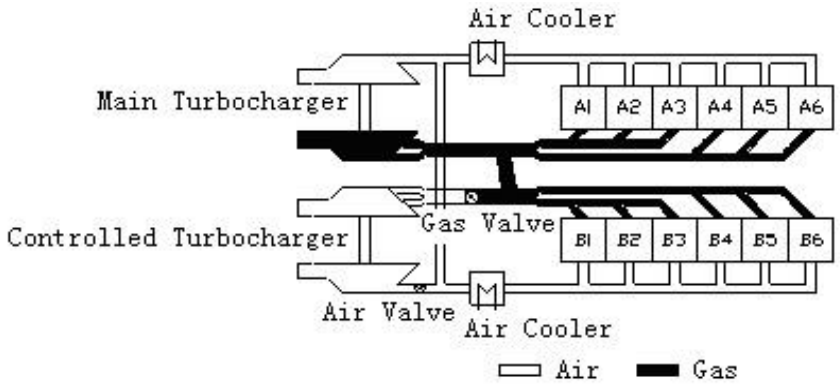


Fig.1. Structure sketch of the sequential turbo-charging system

The measure system is composed of the diesel engine parameters module, turbo-charging system parameters module and PM measuring module. The diesel engine performance parameters include heat release rate, cylinder pressure, and engine speed and fuel consumption. The turbo-charging system parameters include turbocharger speed and compressor pressure. PM emission values are measured by AVL 439 instrument. The main equipments used in experiment are given in Table 2.

Table.2

Experiment Equipments

Dynamometer machine	Nan feng	CW160
Engine automatic control system	Xiang yi	FC2000
Fuel consumption instrument	Xiang yi	C2210
PM emission instrument	AVL	439
Combustion analyzer	AVL	621
NO_x instrument	HORIBA	EXSA.240CL

3. Experimental Scheme

It is well known that the main and the controlled turbochargers are switch-in based on the engine operation conditions in the sequential turbo-charging system. The engine speed for the STC system switching is determined through the switching experiments of the STC system. It is found that the engine speed at proper switching condition is 1429r/min. In the transient switching experiments, the diesel engine performance parameters and PM emission are measured when the delay time Δt of the air valve open later than the gas valve are 0s,0.5s ,1.5s and 2.5s during the controlled turbocharger switch-in process. The experiments time of every case is 30s. The gas valve is open first when the engine has operated for 10s, then the air valve is open subsequently according to the different delay time. Table 3 is the experiment scheme.

Table.3

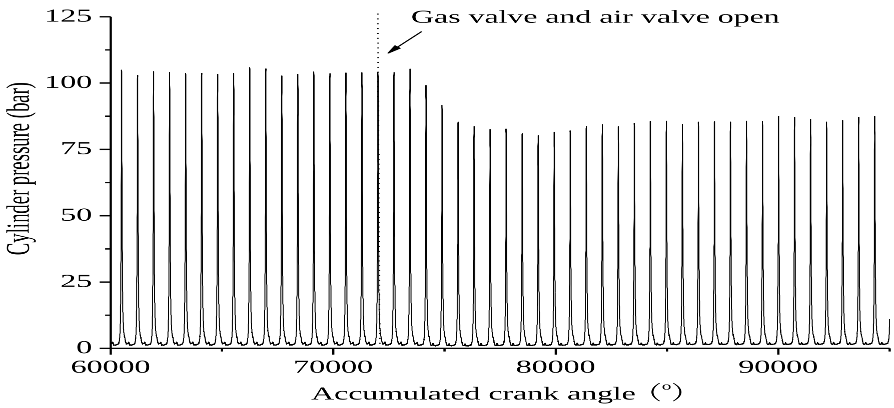
Experiment scheme

Controlled turbocharger	Gas valve	Air valve	Delay time
Switch-in	open	open	0s
Switch-in	open	open	0.5s
Switch-in	open	open	1.5s
Switch-in	open	open	2.5s

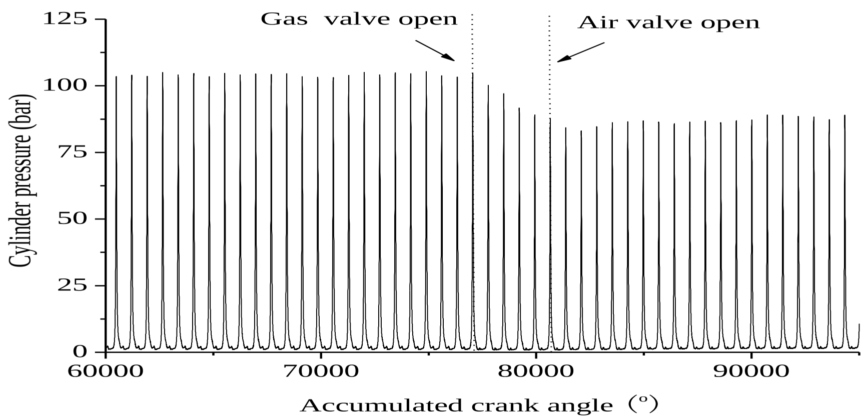
4. Experimental results

Cylinder pressure

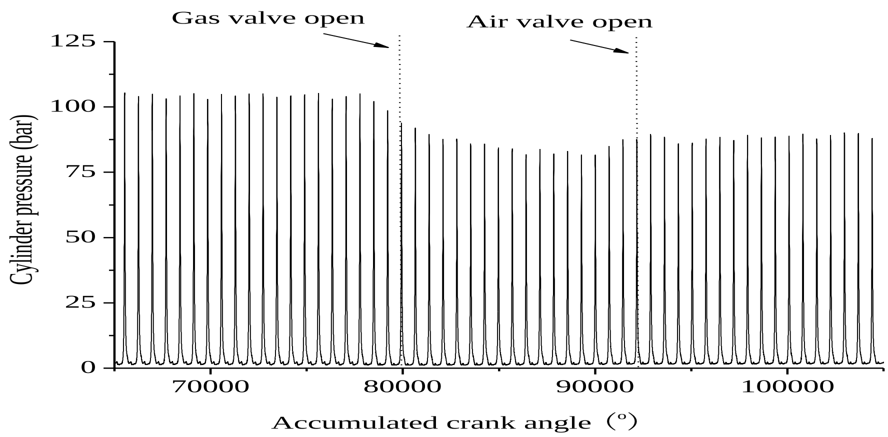
The cylinder pressure of the controlled turbocharger switch-in process is used for analyzing the changes of cylinder pressure. Fig.2 (a,b,c,d) presented the changes of cylinder pressure at variable switching delay time for the engine at switching conditions. It can be seen from the below Figs that the cylinder pressures of the 1TC are 105 bar and that of the 2TC is 89 bar. The cylinder pressure is increasing significantly at1TC condition**(16%increase)**. Moreover, it is also can be seen that the cylinder pressures of the variable delay time are stable before the gas valve opens.



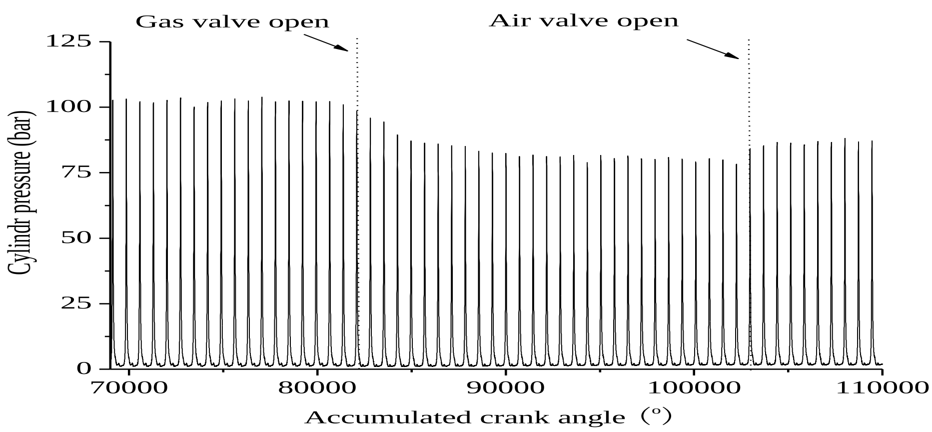
(a) Δt=0s



(b) Δt=0.5s



(c) Δt=1.5s



(d) Δt=2.5s

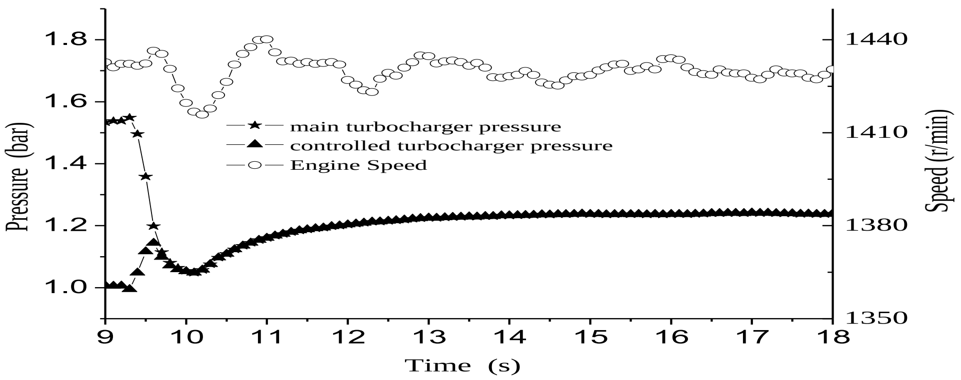
Fig.2. Cylinder pressure at different delay time

Comparing the changing trend of the cylinder pressure among the cases ($\varDelta t$=0s, 0.5s, 1.5s and 2.5s) in transient switching experiments, it is shown that the case $\varDelta t$=0.5s is shorter than that of other cases when the cylinder pressure returns to stable. Moreover, with the switching delay time increases, the wave time of the cylinder pressure is longer, especially the case $\varDelta t$=2.5s. From the Fig. 2(d), it is also shown that the maximum cylinder pressure has fallen below 80 bar and maintained for 20 cycles. Therefore, it is not reasonable to keep the delay time of air valve open too long.

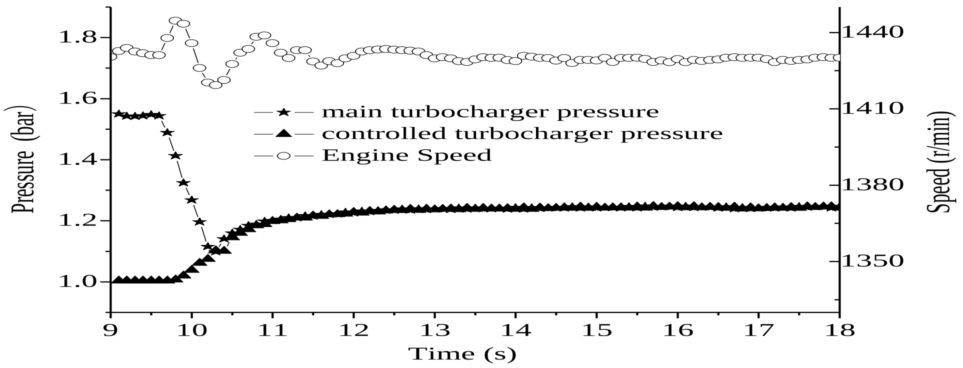
Turbocharger pressure and Engine speed

In order to compare the differences of turbocharger performance among the cases, the main turbocharger pressure, the controlled turbocharger pressure and engine speed are analyzed. Fig. 3 (a,b,c,d) show the turbocharger pressure and the engine speed at variable switching delay time in the switching condition.

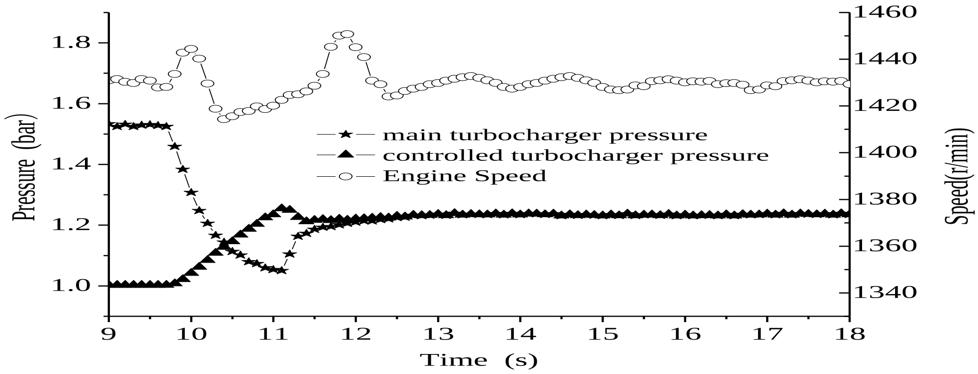
It is shown from the Fig.3, in the different delay time of the switching process besides the case $\varDelta t$=0s, the longer the switching delay time, the more the engine speed waved, the more the pressure of the main turbocharger dropped and the longer time to return the target engine. Moreover, the dropping extent and recovery time of the turbocharger pressure and engine speed of the case $\varDelta t$ =0.5s are less than that of other cases. However, Fig. 3 (a) shows that the air reversed flow appeared in the controlled turbocharger when the air valve and gas valve are open simultaneously and the engine speed waved more than the case $\varDelta t$ =0.5s . The reason is that the controlled turbocharger from cold condition to the normal operation need overcome inertia and the compressible characteristics of the air.



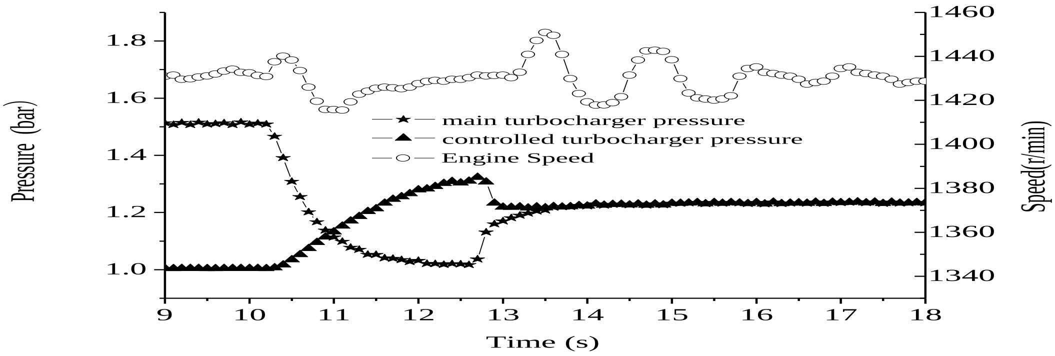
(a) $\varDelta t$=0s



(b) $\varDelta t$=0.5s



(c) $\varDelta t$=1.5s



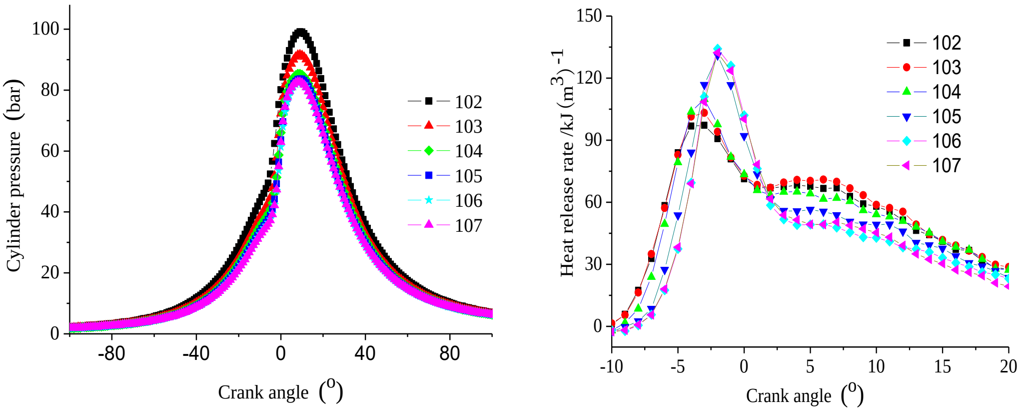
(d) $\varDelta t$=2.5s

Fig.3. Engine speed and pressure after compressor with different delay time

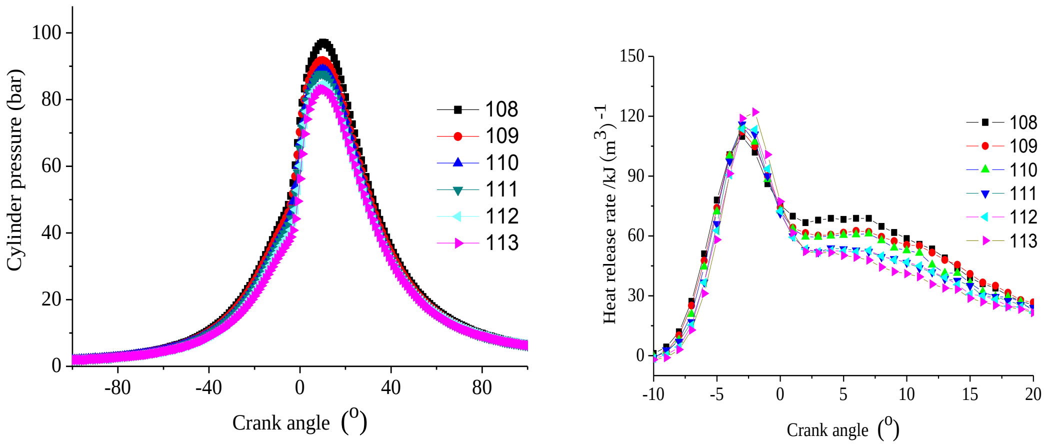
Heat release rate

In order to study the combustion characteristics of a turbocharged diesel engine during transient switching, the combustion heat release rate curves with different switching delay times are compared. The staring time of switching delay is controlled by manual operation, so the engine cycles numbers at each switching delay is slightly different.

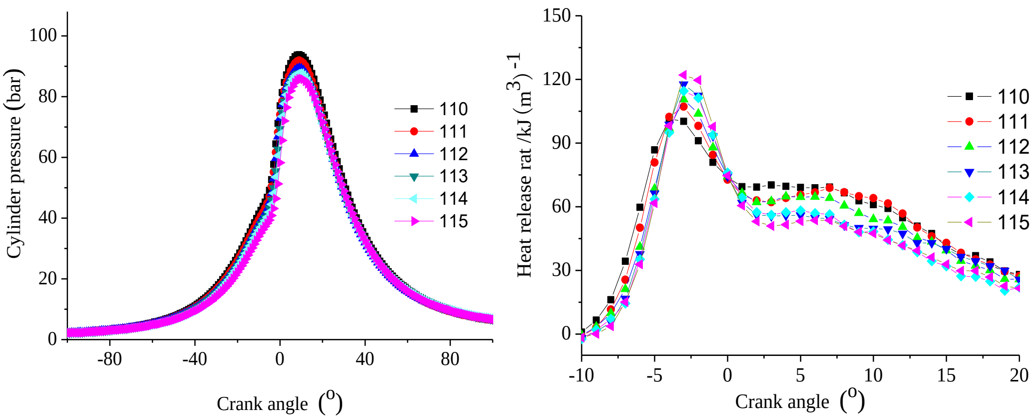
Fig.4(a,b,c,d) show that the cylinder pressure significantly decreased and the peak of the cylinder pressure appears after the top dead center when the gas valve opens. It is also shown that the peak value of the cylinder pressure curve corresponds to the diffusion combustion stage, comparing with the heat release rate curve.



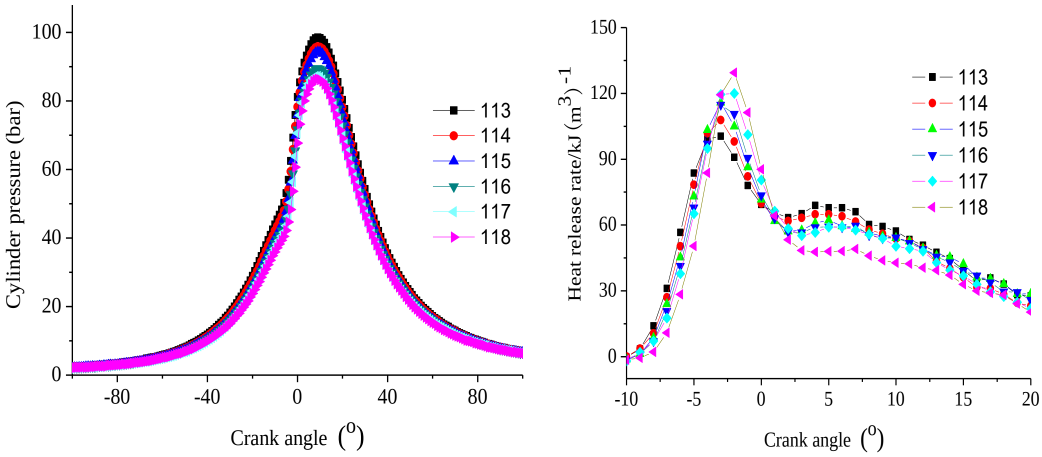
(a) Δt=0s



(b) Δt=0.5s



(c) $\varDelta t$=1.5s



(d) $\varDelta t$=2.5s

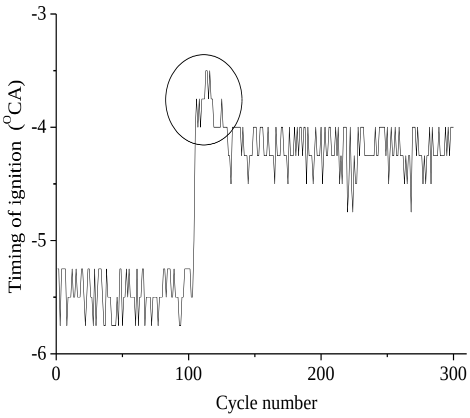
Fig.4. Cylinder pressure and heat release at different delay time

The heat release rate curves show that the maximum premixed combustion release rate all increased in the controlled turbocharger starting process. Moreover, the diffusion combustion stage release rate all decreased. At the same time, the ignition delay time increased and the starting time of combustion delayed. The reason is that the gas valve of controlled turbocharger is first opened and the main turbocharger pressure is continued to decline. Therefore, the combustion in cylinder is deteriorated and the engine speed decreased. The diesel engine governor increased the amount of fuel injection repeatedly for maintaining a stable speed and that lead to the peak of the premix release rate is increased.

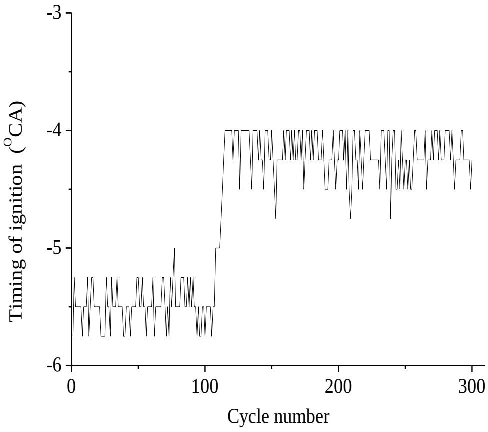
Timing of ignition

Fig.5 shows the timing of combustion curves at different delay time. The abscissa is the numbers of transient test cycles. As can be seen from Fig.5, compared to the timing of combustion of 1TC (-5.5°CA), that of 2TC is -4°CA, the ignition delay of 2TC is longer than that of 1TC.This is likely the cylinder pressure and excess air coefficient of the 1TC are greater than that of 2TC at the time of the fuel injected and the cylinder combustion conditions of 1TC is better than that of 2TC.

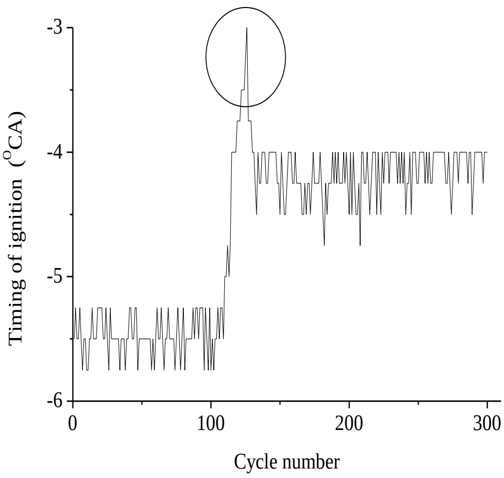
Compared the timing of ignition of the different switching delay time, in addition to Fig.5(b), the other time of ignition are late. With the longer of switching delay time, the duration of ignition timing late is more (such as the circle shown in Fig.5), when switching delay time is 2.5s, the timing of ignition has delayed to-3 °CA.



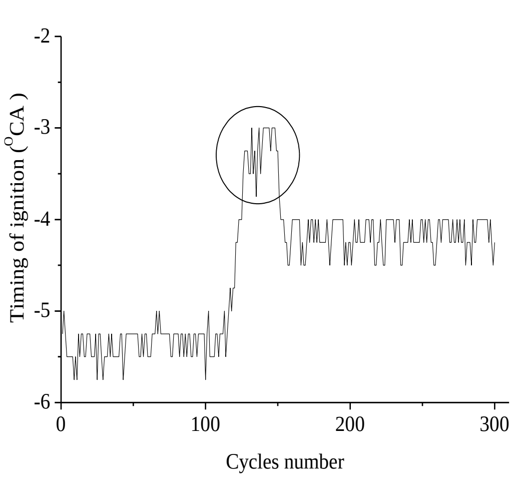
(a) Δt=0s



(b) Δt=0.5s



(c) Δt=1.5s



(d) Δt=2.5s

Fig .5. Timing of combuStion curves at different delay time

PM and NO_x emissions

Fig.6 presents the concentration of PM at variable switching delay time in switching condition. The four lines denote the transient PM emission of the different switching delay time. Fig.7 presents the NO_x emissions at switching condition. Fig.8 presents the Peak vale of PM emissions with different delay time.

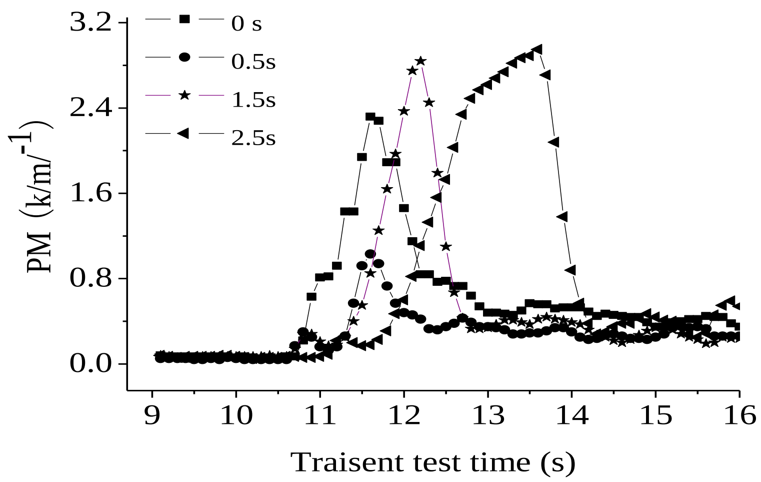


Fig.6. PM Emissions with different delay time

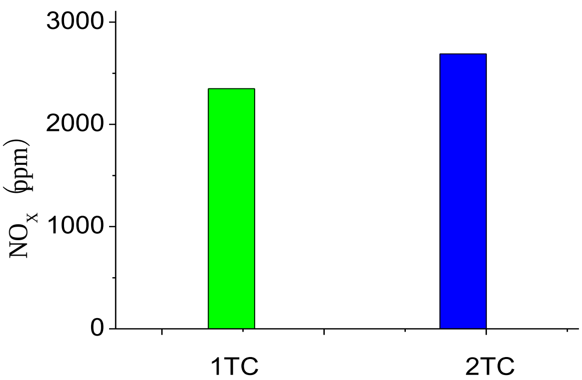


Fig.7 Comparison of measured value of NO_x emissions at switching condition

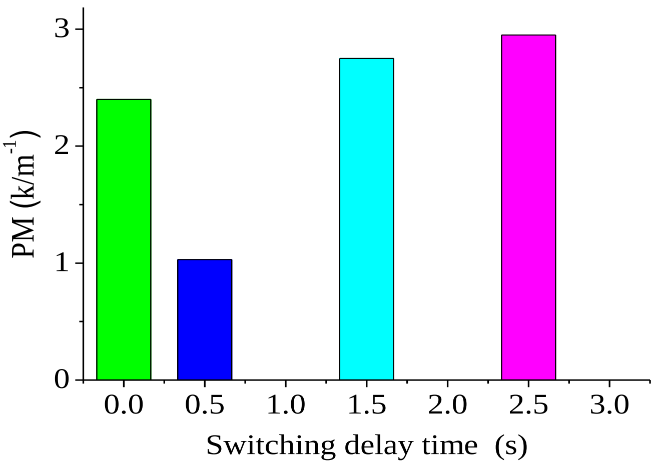


Fig.8. Peak vale of PM with different delay time

It is shown that the PM emissions are 0.02 k/m^{-1} in 1TC and that of 2TC are 0.1 k/m^{-1}. The PM emissions in 1TC declined significantly. As can be seen, with the switching delay time increases from 0.5s to 2.5s, a significant improvement of the PM emission appears in the Fig.6. Moreover, with the switching delay time increases, the duration time of the PM peak prolonged correspondingly. When the switching delay time is 2.5s, the duration time of the PM peak increased to 3s showed in Fig.6. Fig.7 is shown that the NO_x emissions are 2400ppm in 1TC and that of 2TC are 2700ppm. The NO_x emissions in 1TC descend obviously.

As Fig.8 shown, compare with the 0.5s case, the PM emissions peak of the 0s case increases to 2.45 k/m^{-1}. These results show that the proper switching delay time is very important, too long or short of that will make the PM emissions worse. Based on the experiment results mentioned above, considering that the smooth switching process is realized, so the best delay time of air valve open later than the gas valves is 0.5s .

5. Conclusions

In the switching condition of the diesel engine, the engine performances can be increased by the 1TC condition. Compared with the 2TC condition, the highest cylinder pressure improvement is 16% and the declining extreme value of the PM emissions is about 75%. The heat release rate curves of each switching delay time show that the maximum premixed combustion release rate all increased in the controlled turbocharger switch-in process and the diffusion combustion stage release rate all decreased. At the same time, the ignition delay increased and the starting time of combustion delayed. The transient switching experimental results show that the surge would be occurred in compressor and large variation of intake pressure of diesel engine would present when valves are simultaneously open.

However, if the delay time is too long, it will lead to the engine speed wave worsen. Optimal control strategy of the opening during the switch-in process of control turbocharger under a switching point is obtained. During the controlled turbocharger switch-in process, the air valve should open 0.5s later than the gas valve. This strategy can effectively reduce the PM emissions in the transient switching process.

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